Design of a Ku-Band Single-layer Broadband Circularly Polarized Reflectarray Antenna

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Abstract: In this paper, a Ku-band broadband single-layer reflectarray antenna with Left-Hand Circularly Polarization (LHCP) is presented. Radiation elements of the reflectarray are gapped-ring that set on the surface antenna with a variable angle to form an arbitrary radiation pattern. First, a radiation element with 0.74×0.7 λ dimensions at the central frequency (15 GHz) is designed and simulated using Floquet port in HFSS software. In the whole band, the co- and cross-polarization reflection coefficients are 0 dB and less than -15 dB, respectively. Also, results of the phase of the reflected wave show that the designed unit cell with variable angles of the radiation element generates the very smooth linear phase curve with a gentle slope. Therefore, this unit cell is proper for broadband reflectarray antenna design. Second, the set of the gapped ring with variable angles constitute the reflectarray antenna with dimension 4.9 λ × 4.9 λ. The array is simulated with HFSS software. Results show that the difference of between co- and the cross-polarization level is more than 13 dB at whole Ku-band. However, the 3-dB axial-ratio (AR) and 1-dB gain bandwidths are 40% and 25%, respectively.

Keywords: Angular rotation technique, Broadband circular polarization, Reflectarray antenna, Single-resonance.

I. INTRODUCTION

A reflectarray antenna is a flat surface, which consists of discrete radiation elements. The excitation of the reflectarray is carried out by an antenna which has been set in front of it. It is clear that physical distance from feed to each radiation element on the surface of the antenna is different. Therefore, it is necessary to form a desired radiation pattern, each radiation creates proper reflective phase to compensate for the different spatial phase delay. The reflectarray has been preferred on parabolic reflectors and phased array antennas because of some advantages such as its flat surface, low-profile, easy implementation and no requirement to the complicated feed network. Despite known advantages of reflectarrays, they suffer from narrow bandwidth. The bandwidth of printed reflectarrays is limited by two factors: the narrow bandwidth of the radiation elements and the differential spatial phase delay.

To enhance the bandwidth, some methods have been introduced in the literature such as using of the thick and low dielectric constant substrate, stacked multi-layer structures with variable size patches multi-resonance radiation element [1], and aperture-coupled patch structures multi-resonance radiation element. Because the multi-layer antennas are costly and difficult to implement, the single-layer structures that lead to wide bandwidth, are usually more attractive.

Another limiting factor of bandwidth originates from differential spatial phase delay. Since the spatial phase compensation of each element is fixed for the central frequency, the variation of frequency causes a frequency excursion error in the radiated wave phase [1]. Approaches such as using of true-time delay lines [3] and the design of the reflectarray with larger ratio focal length (f) to the antenna diameter (D), help us to reduce the amount of frequency excursion error [1].

One of the important challenges in the reflectarray antenna is the design of the radiation element. As mentioned before, to make the radiation pattern in the desired orientation, it is necessary to generate proper phase by radiation elements depending on their position relative to feed. Techniques such as the use of the variable size patch [4], the variable stub length [5] and the element rotation [6, 7] are conventional to generate different phase by radiation elements. Three items that must be considered in the utilized techniques are: 1) The produced phase range; the least required phase range must be between 0°-360°. 2) The slope of phase curve versus variation of size or stub length or rotation angle of the element; It is necessary that the slope of phase curve be fix and minimum. Otherwise, manufacturing tolerances can severely influence the antenna results. 3) Variation of the produced phase versus variation of the frequency; Variation must be linear to avoid the radiated signal distortion.

Today, the circular-polarization (CP) because of its robustness against environmental conditions has been preferred in many communication applications. Various CP reflectarrays have been proposed in the literature [6, 8, 9]. The introduced radiation elements are cross-dipole...
elements [8], gapped ring [2] and non-traditional shape elements [10]. Among them, the gapped ring element has several advantages such as compact size, broader CP bandwidth and little blockage in the incident field of multilayer structures [11]. When the gapped ring is utilized, the phase compensation can be achieved by changing the ring sizes or the rotation of the elements relative to one reference. In the rotation of the elements technique, all radiation elements have identical size and resonance frequency that makes the design and fabrication of the reflectarray easier than other methods. There is a 2:1 ratio between the element reflective phase and angular rotation, as a $\psi^0$ element rotation leads to a $2\psi^0$ phase delay compensation. Therefore, the phase variation ranges are limited to less than $360^\circ$. However, this subject is a known drawback but this technique generates an independent frequency compensate phase delay [12] leads to the broadband antenna.

In this paper, a broadband single-layer gapped ring CP reflectarray antenna is designed and analyzed for Ku-band applications. The paper is organized as follows: section 2 describes the design an analysis of unit cell; the design and analysis of array are presented in section 3, and concluding remarks are given in section 4.

II. DESIGN AND ANALYSIS OF UNIT CELL

A. Design of unit cell

Usually, for simplifying of the analysis of the reflectarray antenna, the infinite array model is used. Therefore, by applying the Floquet’s theorem, the analysis is reduced to only one periodic cell. Here, the unit cell is a square with the dimension of $0.7\lambda_0 \times 0.7\lambda_0$ (at 15 GHz) that gapped ring patch is printed on the substrate as shown in Fig.1. The outer radius of the ring ($R_1$) is 4.5mm. The used substrate is Rogers RT/duriod 5880 (tm) with dielectric constant 2.2, losses tangent ($\delta$) of 0.0009 and the thickness of 1.575mm. Additionally, an air/foam layer with thickness $h=1$ mm is inserted between the substrate layer and the ground plane to enhance the linearity of the reflection phase curve.

In Floquet port of the HFSS software, the master/slave boundaries model periodic boundary conditions for the unit cell. On the other hand, the unit cell behaviors such as reflection phase curve.

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$$\begin{bmatrix} E_{x}^{\text{inc}} \\ E_{y}^{\text{inc}} \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} E_{x}^{\text{ref}} \\ E_{y}^{\text{ref}} \end{bmatrix},$$  \hspace{1cm} \text{(1)}$$

where, $E_{x}^{\text{inc}}$, $E_{y}^{\text{inc}}$, $E_{x}^{\text{ref}}$ and $E_{y}^{\text{ref}}$ are x- and y-polarized components of the incident and the reflective electric fields, respectively. As a result, the total reflective electric field can be written as:

$$\tilde{E}_{\text{ref}} = E_{x}^{\text{ref}} \hat{x} + E_{y}^{\text{ref}} \hat{y} = (S_{11}E_{x}^{\text{inc}} + S_{12}E_{y}^{\text{inc}}) \hat{x} + (S_{21}E_{x}^{\text{inc}} + S_{22}E_{y}^{\text{inc}}) \hat{y},$$  \hspace{1cm} \text{(2)}$$

Eq. (2) can be rewritten as in (3):

$$\tilde{E}_{\text{ref}}^{\text{inc}} = \frac{1}{2} \left( (S_{11}E_{x}^{\text{inc}} + S_{12}E_{y}^{\text{inc}}) \hat{x} + j(S_{21}E_{x}^{\text{inc}} + S_{22}E_{y}^{\text{inc}}) \hat{y} \right) + \frac{1}{2} \left( (S_{11}E_{x}^{\text{inc}} + S_{12}E_{y}^{\text{inc}}) \hat{x} - j(S_{21}E_{x}^{\text{inc}} + S_{22}E_{y}^{\text{inc}}) \hat{y} \right)$$  \hspace{1cm} \text{(3)}$$

For LHCP incident wave in which the direction of propagation is $(-z)$, $\tilde{E}_{\text{inc}}^{\text{inc}}$ can be written as:

$$\tilde{E}_{\text{inc}} = E_{0}(\hat{x} - j\hat{y})e^{j\beta},$$  \hspace{1cm} \text{(4)}$$

By replacing $E_{x}^{\text{inc}} = E_{0}$ and $E_{y}^{\text{inc}} = -jE_{0}$ in (3), it is rewritten as:

$$\tilde{E}_{\text{total}} = \frac{E_{0}}{2} \left( (S_{11} - jS_{12}) \hat{x} + j(S_{21} - jS_{22}) \hat{y} \right) + \frac{E_{0}}{2} \left( (S_{11} - jS_{12}) \hat{x} - j(S_{21} - jS_{22}) \hat{y} \right)$$  \hspace{1cm} \text{(5)}$$

Therefore, the co- and cross-polarized components of reflection coefficients are expressed as follow:

$$\Gamma_{\text{co}} = \frac{\Gamma_{\text{ref}}}{\Gamma_{\text{inc}}} = \frac{1}{2} \left( (S_{11} - jS_{12}) - j(S_{21} + S_{22}) \right)$$

$$\Gamma_{\text{cross}} = \frac{\Gamma_{\text{ref}}}{\Gamma_{\text{inc}}} = \frac{1}{2} \left( (S_{11} + S_{22}) + j(S_{21} - S_{12}) \right)$$  \hspace{1cm} \text{(6)}$$

Fig. 1. The geometry of the unit cell of the CP reflectarray, $c=1.6$mm, $w=2.3$ mm, $R=4.5$ mm, $h=1.575$ mm, and $h=1$ mm.

The designed unit cell is simulated by Floquet port of the HFSS software. The incident plane wave of Floquet port is normal to the unit cell of Fig. 1. In fact, the rotation angle of the gapped ring is assumed to be zero degrees in this figure. The magnitude and phase of the co- and cross-polarization reflection coefficient versus frequency have been plotted in Fig. 2. As shown in Fig.2(a), 0dB co- and less than -15dB cross-polarization reflection coefficient
level have been obtained. Fig. 2(b) presents the reflected phase curve of unit cell versus frequency. It is obvious that the curve is has a gentle slope so that a 1 GHz frequency deviation leads to a ±20° phase shift of the co-polarized component phase. Therefore, it can be concluded that this unit cell will be resistant to manufacturing tolerances and suitable for broadband reflectarray. In the next stage, assuming a constant frequency, the printed gapped ring is rotated gradually and the obtained phase of the reflected wave is recorded. The results are plotted in Fig. 3. As observed, by variation of the rotation angle, obtained curves are perfectly linear. As a result, the broadband ability of this unit cell is again proven. Also, Fig. 3 shows that there is approximately a 1:2 ratio between the broadband ability of this unit cell and the required phase compensation of each element of a reflectarray to achieve the uniform phase distribution across this imaginary plane [15]. Mathematically, it is written by:

$$-\phi_{d}d_{mn} + \phi_{s} = 2k\pi, \forall \begin{array}{l} m = 1,2,...,M \\
 n = 1,2,...,N \end{array}$$

where, $k_0 = \text{wave number in free space}$, $d_{mn} = \text{physical distance from the feed to each element}$, $s_{mn} = \text{physical distance from the (m,n)\textsuperscript{th} element to the imaginary plane}$, $\phi_{mn} = \text{amount of phase shift of (m,n)\textsuperscript{th} reflectarray element}$, and $M \times N = \text{number of elements in the array}$. For a 2D planar array of $M \times N$ elements lying in the $xy$ plane, to form a pencil beam in $(\theta_0, \varphi_0)$ direction, it is necessary that:

$$-k_0 d_{mn} + \phi_{mn} = -k_0 \left[ x_{mn}' \cos \theta_0 + y_{mn}' \sin \varphi_0 \sin \theta_0 \right]$$

where $x_{mn}'$ and $y_{mn}'$ are components of location vector of $(m,n)\textsuperscript{th}$ radiation element, respectively. Since it is clear, the required phase compensation of each element of reflectarray $\phi_{mn}$ is achieved using (8).

**B. Design of array**

Fig. 4 shows the side view of the reflectarray. As seen, to form a pencil beam in $(\theta_0, \varphi_0)$ direction at a frequency of $f_0$, it is necessary to create p-p' co-phase imaginary plane that is normal to the beam direction. Since the physical and electrical distance from feed to each element and each element to p-p' imaginary plane are different, so each patch radiation must produce proper phase to achieve the uniform phase distribution across this imaginary plane [15].

**III. SIMULATION AND RESULTS**

The purpose of this paper is the design of LHCP reflectarray to produce a beam in orientation $(\theta_0, \varphi_0) = (30^\circ, 0^\circ)$ in the Ku-band. First, a $7 \times 7$ LHCP reflectarray has been proposed. The location of the antenna feed is set in the center of the reflectarray and the focal length to diameter ratio (F/D) of the antenna is supposed to be 1.5. By using (8), the required phase compensation of each element of the reflectarray and the amount of the rotation angle of the gapped ring is calculated. Fig.5(a) shows the necessary phase for each element. The designed reflectarray antenna is simulated and fabricated as shown in Fig.5(b).
The 3D view of the simulated radiation pattern of the designed antenna is depicted in Fig. 6. (a), at the operation frequency of 15 GHz. Since it was not possible to test the reflectarray performance at 15 GHz, the measurement is done at 12 GHz. Fig. 6. (b), shows the comparison between 2D power radiation pattern of the simulation and the measurement. There is some deviation between the simulation and the measurement results. This deviation originates from improper test conditions such as LHCP feed condition. The comparison between the co- and cross-polarized components, at the operation frequency, is shown in Fig. 7. (a). As seen, the difference between co- and cross-polarized components are at least -30dB in the main lobe. To evaluate the stability of the radiation pattern, the array simulation is also performed at 12 GHz and 17 GHz. The obtained 2D power radiation pattern is depicted in Fig. 7.

As expected, the radiation pattern has been rotated with frequency variation. This angle deviation is approximately in the whole Ku-band. As plotted in Fig. 8. (a), 1-dB gain and 3-dB axial-ratio bandwidth have obtained 25% and 40%, respectively. Besides, 25% of overlap is achieved in 1-dB gain and 3-dB axial-ratio bandwidths. Also, the comparison of co- and cross-polarized component at whole
Ku-band is accomplished and shown in Fig. 8. (b). The amount of difference is at least -13 dB in (30°, 0°) direction.

IV. CONCLUSIONS

In this paper, the design and simulation of a LHCP reflectarray antenna were accomplished. In order to form a radiation pattern in the desired direction, the spatial phase compensation was done by the element rotation method.

The results showed that the reflected wave characteristics, either magnitude or phase, for the proposed unit cell of the reflectarray, are well in Ku-band. Therefore, it is proper for wideband applications. Also, the reflectarray simulation showed that 1-dB gain and 3-dB axial-ratio bandwidth obtain 25% and 40%, respectively. Finally, there was good agreement between the simulation and the measurement results.

REFERENCES